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RESEARCH MEMORANDUM

INJECTION PRINCIPLES FOR LIQUID OXYGEN AND HEPTANE USING NINE-ELEMENT INJECTORS IN AN 1800-POUND-THRUST ROCKET ENGINE

By Richard F. Neu

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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RESEARCH MEMORANDUM

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SUMMARY

Six nine-element injectors were studied for the liquid-oxygen - heptane propellant system in an 1800-pound-thrust rocket engine. These injectors featured three different orientations of three basic injector element types. This work is an extension of the single- and two-element injector studies previously reported.

The characteristic velocities for comparable injector types were about the same as those obtained from the two-element study. The level of performance was generally higher for the nine-element injectors. For the parallel-sheets injectors, the decrease in performance due to the interference of like propellant sprays was generally less than for the two-element injectors. Interference of unlike sprays was less detrimental to characteristic velocity performance than like-spray interference.

Combustion instability, frequently encountered with single-element injectors but not present in two-element injectors, did not appear during this nine-element study.

INTRODUCTION

Scaling has been recognized as one of the major problems confronting rocket designers (refs. 1 to 3). The concept of a basic injector element that would lend itself to scaling the injector simply by increasing or decreasing the number of such elements (ref. 1) has been introduced in the rocket industry. Following this concept, the NACA has investigated several different types of single-element injectors in engines of 200-pound thrust. Three propellant combinations were used: liquid oxygen - heptane; liquid oxygen - gaseous hydrogen; and 85-percent-liquid-oxygen - 15-percent-liquid-fluorine - heptane (refs. 4 to 6). These past investigations evaluated the relative importance of the atomization and mixing processes and determined the influence of physical and chemical properties on performance. The applicability of these findings to multielement arrangements

was studied in reference 7 where two-element injectors were investigated for liquid-oxygen - heptane propellants in a 400-pound-thrust engine.

In this report, nine-element injectors were studied for the liquid-oxygen - heptane propellants to determine if the trends observed in the two-element study apply as the number of elements is increased. This investigation determines (1) if like propellant spray interference has a similar effect on performance as it did in the two-element study, (2) how the individual performance levels of the nine-element injectors compare with corresponding performance levels from the two-element study, and (3) if combustion instability would occur in these nine-element engines.

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Three basic injector element types were used: parallel-sheets elements, which atomized the propellants but did not mix them; impinging-sheets elements, which atomized the propellants before mixing them; and impinging-jets elements, which simultaneously atomized and mixed the propellants. All three had been investigated during the two-element study (ref. 7).

APPARATUS AND PROCEDURE

Rocket Engines

Two rocket engines were used during this study: a water-cooled engine and an uncooled engine with a solid copper nozzle (fig. 1). The solid chamber consisted of two cylindrical sections between which a transparent plastic ring was placed about 2 inches from the injector face. This ring permitted high-speed streak photographs to be taken of the combustion process in order to determine the presence of combustion instability.

The engines were designed for a nominal thrust level of 1800 pounds at a chamber pressure of 300 pounds per square inch. The chamber diameter was 6 inches, and the over-all chamber length (chamber plus nozzle) was 11 inches for each engine. No nozzle divergence section was used. The throat diameter was 2.36 inches and the contraction ratio was 6.5. Propellants were ignited by a 3/8-inch spark plug located in the injector face.

Element Types

Three of the four basic injector element types investigated in the two-element study were used in this investigation. They are: (1) parallel-sheets element (atomization without mixing), (2) impinging-sheets element (atomization before mixing), and (3) impinging-jets element (simultaneous atomization and mixing).

The same injector body was used for both the parallel-sheets and the impinging-sheets elements (fig. 2). The detail of these elements is shown in figure 3. For the parallel-sheets element, the propellant deflector plates were located and shaped to produce two oxidant sprays and one fuel spray, each spray being parallel to the other two sprays and perpendicular to the injector face so that they theoretically never intersected. The impinging-sheets element was very similar except that both oxidant sprays were angled 10° so that they intersected the fuel spray about 1.2 inches from the injector face. In the case of the impinging-jets element, two oxidant jets impinged upon a fuel jet at 45° angles, the fuel jet being perpendicular to the injector face (see detail, fig. 4).

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Element Orientations

Three element orientations were investigated. The butt interference orientation (fig. 5(a)) was the same as that of the two-element study. In both studies the propellant sprays or fantails from one element butted against like sprays from an adjacent element. The 27° orientation (fig. 5(b)) featured minimum interference between like propellant sprays and approached the parallel orientation of the two-element study. The 12° orientation (fig. 5(c)) had no counterpart in the two-element investigation; it produced maximum interference between unlike propellant sprays. In this case the fuel spray of one element interfered with the oxidant spray of an adjacent element.

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Performance Measurement

Injector performance is reported in terms of characteristic velocity c^* as a function of the mixture ratio. These performance parameters were obtained from measurements of the chamber pressure and the oxidant and fuel flow rates. Chamber pressure was measured at the chamber wall very near the injector with a strain-gage-type pressure transducer. Flow rates were measured by rotating-vane-type flowmeters. Since the liquid-oxygen tank was uncooled, a thermocouple was placed in the oxidant line to measure oxidant temperatures and, hence, densities.

Combustion instability was determined by means of high-speed streak photographs taken of the combustion process occurring within the rocket engine.

Test Procedure

The characteristic velocity was determined for each injector for an oxidant-to-fuel weight ratio range of about 2.0 to 3.0. The run time was about 1.8 seconds, and, as nearly as possible, the total propellant flow

rate was maintained constant at 8.1 pounds per second during each test firing. Each test run was performed with a 0.20-second fuel lead and a 0.15-second oxidant override.

RESULTS AND DISCUSSION

The curves for the characteristic velocity performance (hereinafter designated by c*) for the nine-element injectors and comparable single- and two-element injectors (reproduced from refs. 4 and 7) are presented in figures 6 to 8. Average performance values within the oxidant-fuel weight (mixture ratio) range of 2.0 and 3.0 were determined from these curves and are listed in table I.

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Performance of Nine-Element Injectors

Parallel-sheets injectors (atomization without mixing). - The c* performance curves for three orientations of the parallel-sheets injectors are shown in figure 6(a). The c* performance of the 27° orientation was about 86 percent of theoretical. This performance level decreased about 3 percent with a 12° orientation and 9 percent with a butt orientation (table I).

The reason butt orientation has low performance is probably because large drops form at the point of interference of like fantails (fig. 5(a)).

Higher performance may be expected when interference occurs between unlike propellant sprays, as exemplified by the 12° injector. Here mixing occurs which was absent in the butt-oriented case. It should be noted, however, that the number of spray interference zones for the 12° injector is two-thirds that for the butt injector (figs. 5(a) and (c)). This lesser number of interference zones will also increase the performance level. Therefore, the higher performance level which occurred during unlike spray interference was probably due to two factors: (1) mixing of propellants, and (2) fewer interference zones.

Impinging-sheets injectors (atomization before mixing). - The c* performance of the impinging-sheets injectors was about 91 percent of theoretical for the 27° orientation and 89 percent for the butt orientation as shown in figure 7(a) and table I. Spray interference decreased performance just as it did in the case of the parallel-sheets injectors. This effect was rather small, however, for the impinging-sheets elements (about 100 c* units) where the decrease was caused by interference of mixed propellant sprays.

Streak photographs taken of the inside of the chamber during seven of the test firings indicated no combustion instability.

Impinging-jets injector (simultaneous mixing and atomization). - The c* performance level of the impinging-jets injector with butt interference of sprays approached 96 percent in the lower mixture ratio region (fig. 8(a) and table I). Only one arrangement was studied because, as reported in reference 7, orientation effects are small for injection processes that both mix and atomize the propellants.

High-speed streak photographs taken during nine of the fifteen runs gave no evidence of combustion instability.

Performance comparison. - A comparison of the results of this nine-element injector study (table I) indicates that (1) the parallel-sheets injectors generally gave the poorest performance of the three injection methods studied, (2) the impinging-sheets injectors gave intermediate performance, and (3) the impinging-jets injector gave the highest performance. The importance of mixing the propellants is illustrated by the greater decrease in performance between the impinging-sheets and parallel-sheets injectors than between the impinging-jets and impinging-sheets injectors.

Comparison of Nine- and Two-Element Performance

Performance level. - The c* performance of each nine-element injector is higher than that of the corresponding two-element injector in the low and intermediate mixture ratio regions (figs. 6(b), 7(b), and 8(b), and table I). For the impinging-sheets injector, this performance difference is present also in the high mixture ratio region. A probable reason for this higher performance level might be the longer effective chamber length for the nine-element study (9 in. as compared with 8 in.) due to a larger nozzle volume. For example, if the gas velocity profile curve for the single impinging-sheets injector (fig. 11 of ref. 4) was extrapolated to 9 inches, c* values at 8 and 9 inches are about 5250 and 5400, respectively, as compared with actual characteristic velocity peaks of 5200 and 5400 for the two- and nine-element injectors, respectively. A second reason, probably just as important as the first, is the additional mixing potential and turbulence present in the larger nine-element injectors.

Spray interference. - A performance comparison of the two- and nine-element parallel-sheets injectors shows that in both cases the interference of like propellant sprays causes a decrease in performance (table I). This spread should have remained approximately equal if the conditions present in the two-element study were duplicated in the nine-element study. The spread in performance level between the interfering and non-interfering orientation for the nine-element study, however, was about 40 percent of that for the two-element study. A possible explanation for this difference lies in the greater mixing potential and turbulence levels

associated with the larger combustor as noted in the preceding section. This mixing effect would be expected to increase the performance of the butt orientation more than that of the parallel orientation since, in the former case, the individual sprays are in closer contact. Further, an increase in performance for the 27° orientation would be partially offset by the fact that in this case there were two interference points as illustrated by figure 5(b). These considerations then would lead to a smaller difference in performance for the interfering and noninterfering orientations for the nine-element injectors as compared with the two-element injectors.

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Other factors which could account for the difference in the performance between the interfering and noninterfering orientations in the two studies include: fabrication tolerances which may have caused some misalinement of fantails, rotational misalinement of the elements in the injector body (the probability being greater in the nine-element injectors) which may have prevented precise orientation, and slightly different means of fuel-spray formation (self-impingement of fuel jets for the two-element injectors and fuel jet impingement on a deflector plate for the nine-element injectors). It is believed, however, that the effect of these factors upon performance was rather small, which would probably account for much of the data scatter.

A performance comparison of the two- and nine-element impinging-sheets injectors shows only small differences in performance due to orientation. This result confirms the observation reported in reference 7 that interference effects are small for injection processes that both atomize and mix the propellants. The results from the two studies differ, however, in that with two elements the highest performance was obtained with butt orientation of spray patterns. In this present study, the oxidant sprays were angled less sharply toward the fuel sprays which allowed the sprays to intersect farther from the injector. These elements, therefore, behave in part like the parallel-sheets elements where like propellant spray interference effects were more pronounced.

Combustion oscillations. - The lack of combustion oscillations was in complete agreement with the two-element combustion stability results. The length-to-diameter ratio of the engine used in the nine-element study was smaller than the one used in the single-element study where combustion instability occurred. This factor probably decreased the chances of longitudinal oscillations within the chamber (fig. 4 of ref. 8). It is possible that the arrangement of elements in the larger injectors may have damped any lateral oscillations within the engine.

Observations on Propellant Spray Interference

Like propellant spray interference. - A decrease in performance was noted for the parallel-sheets injectors when like propellant spray

interference occurred for both the two- and nine-element studies. This decrease was appreciably less for the nine-element study. As the injector and engine sizes are increased, it appears that this decrease in performance might be further minimized to the point where like propellant spray interference effects would be negligible for a very large engine.

Unlike propellant spray interference. - In the event that detrimental effects of spray interference are expected, it then appears advantageous to interfere unlike propellant sprays rather than like sprays because of the higher performance level obtained with unlike-spray interference in the nine-element study.

Mixed propellant spray interference. - The interference of spray patterns which contain a mixture of oxidant and fuel produced small effects on performance level for both two- and nine-element injectors. From the performance level standpoint, therefore, it appears that orientation of such elements in multielement injector scaling need not be given major consideration.

SUMMARY OF RESULTS

The interference effects between basic injector elements in a nine-element injector were investigated. The study was performed in a nominal 1800-pound-thrust rocket engine using liquid oxygen and heptane as propellants. A total of six injectors, featuring three different injector element types and three element orientations, was investigated. Characteristic velocity measurements and water-spray photographs were taken.

The following results were obtained:

1. The general level of performance was: (1) parallel-sheets injectors, lowest; (2) impinging-sheets injectors, intermediate; and (3) impinging-jets injector, highest.

2. In the tests of the parallel-sheets injectors, performance with 12° orientation (unlike propellant spray interference) was somewhat lower than the performance with 27° orientation (no propellant spray interference). The performance with butt orientation (like propellant spray interference) was the lowest of the three orientations.

3. In tests of impinging-sheets injectors, the performance with butt orientation was only slightly less (about 100 characteristic velocity units) than that with 27° orientation.

4. No evidence of combustion instability was encountered.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 14, 1957

REFERENCES

1. Ross, Chandler C.: Scaling of Liquid Fuel Rocket Combustion Chambers. AGARD Selected Combustion Problems, II - Transport Phenomena; Ignition, Altitude Behaviour and Scaling of Aeroengines. Butterworths Sci. Pub., 1956, pp. 444-456.

2. Crocco, L.: Considerations on the Problem of Scaling Rocket Motors. AGARD Selected Combustion Problems, II - Transport Phenomena; Ignition, Altitude Behaviour and Scaling of Aeroengines. Butterworths Sci. Pub., 1956, pp. 457-468; discussion by S. S. Penner, pp. 487-488.

3. Penner, S. S.: Rational Scaling Procedures for Liquid-Fuel Rocket Engines. Jet Prop., pt. 1, vol. 27, no. 2, Feb. 1957, pp. 156-161.

4. Heidmann, M. F., and Auble, C. M.: Injection Principles from Combustion Studies in a 200-Pound-Thrust Rocket Engine Using Liquid Oxygen and Heptane. NACA RM E55C22, 1955.

5. Auble, Carmon M.: A Study of Injection Processes for Liquid Oxygen and Gaseous Hydrogen in a 200-Pound-Thrust Rocket Engine. NACA RM E56I25a, 1956.

6. Heidmann, M. F.: A Study of Injection Processes for 15-Percent Fluorine - 85-Percent Oxygen and Heptane in a 200-Pound-Thrust Rocket Engine. NACA RM E56J11, 1957.

7. Heidmann, Marcus F.: Injection Principles for Liquid Oxygen and Heptane Using Two-Element Injectors. NACA RM E56D04, 1956.

8. Maslen, Stephen H., and Moore, Franklin K.: On Strong Transverse Waves Without Shocks in a Circular Cylinder. Jour. Aero. Sci., vol. 23, no. 6, June 1956, pp. 583-593.

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TABLE I. - TWO- AND NINE-ELEMENT INJECTOR PERFORMANCE

[All values listed here are average values (oxidant-fuel ratio range, 2.0 to 3.0) taken from figs. 6 to 8.]

	Two-element injectors		Nine-element injectors	
	Characteristic velocity performance, c^*	Percent theoretical	Characteristic velocity performance, c^*	Percent theoretical
Parallel-sheets injectors:				
27° Orientation[a]	4890	83.1	5065	86.2
12° Orientation	----	----	4870	82.9
Butt orientation	3460	58.8	4520	76.9
Impinging-sheets injectors:				
27° Orientation[a]	5030	85.5	5360	91.2
Butt orientation	5150	87.6	5250	89.3
Impinging-jets injectors:				
27° Orientation[a]	5290	89.9	----	----
Butt orientation	5400	91.9	5490	93.3

[a]27° Orientation of nine-element study corresponds to parallel orientation of two-element study.

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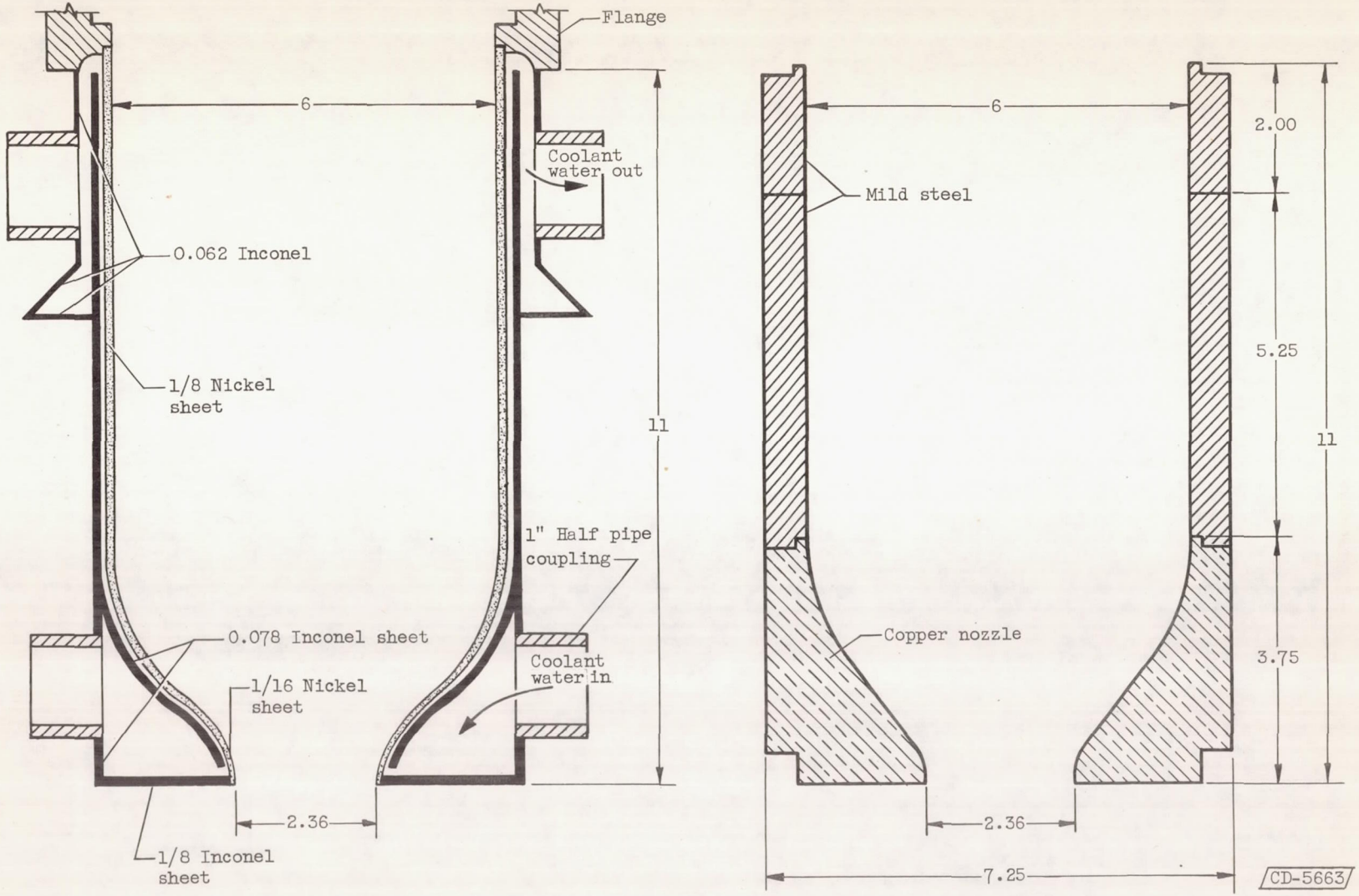


Figure 1. - Engines. (All dimensions in inches.)

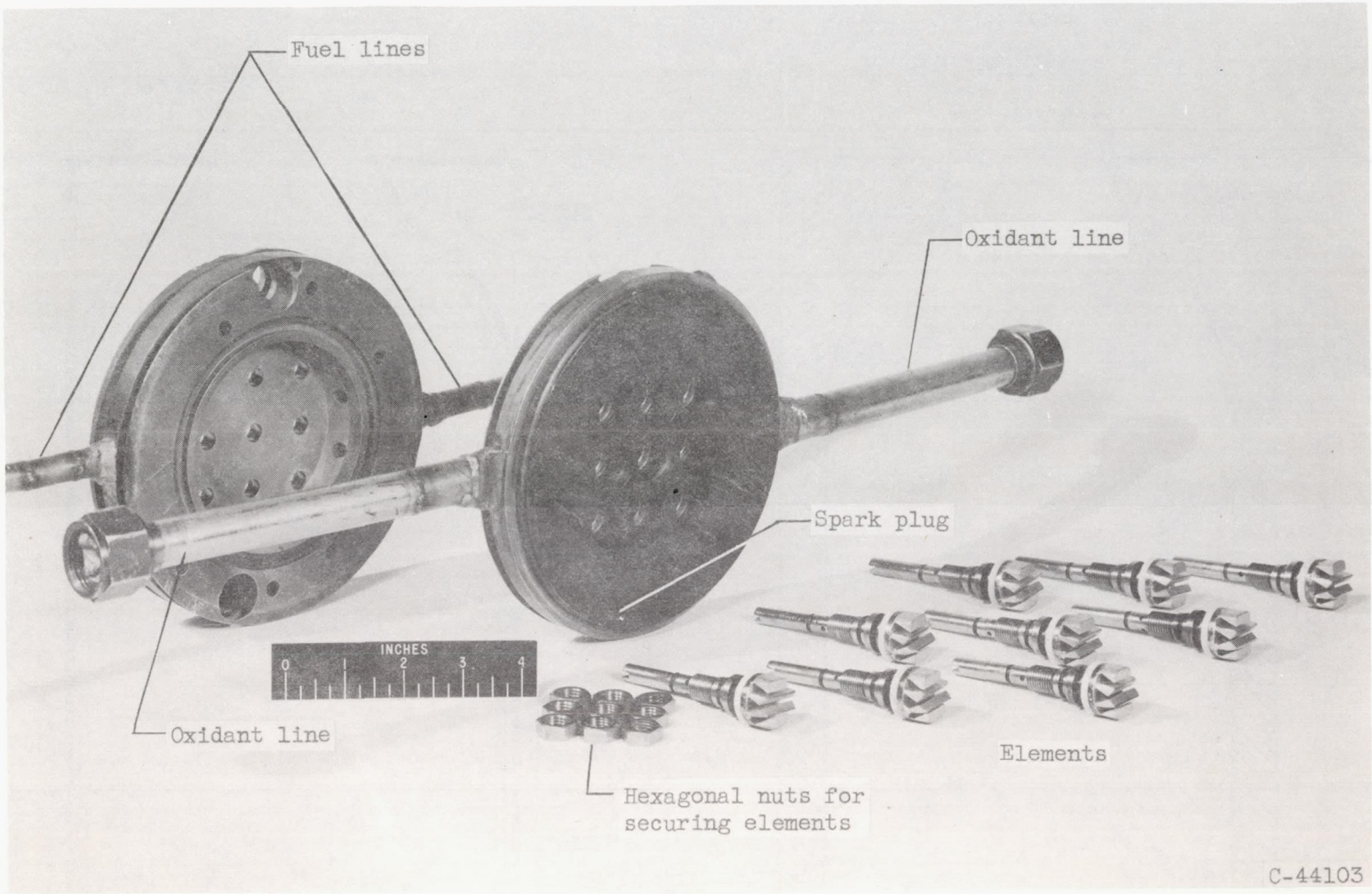


Figure 2. - Exploded and assembled views of nine-element injector.

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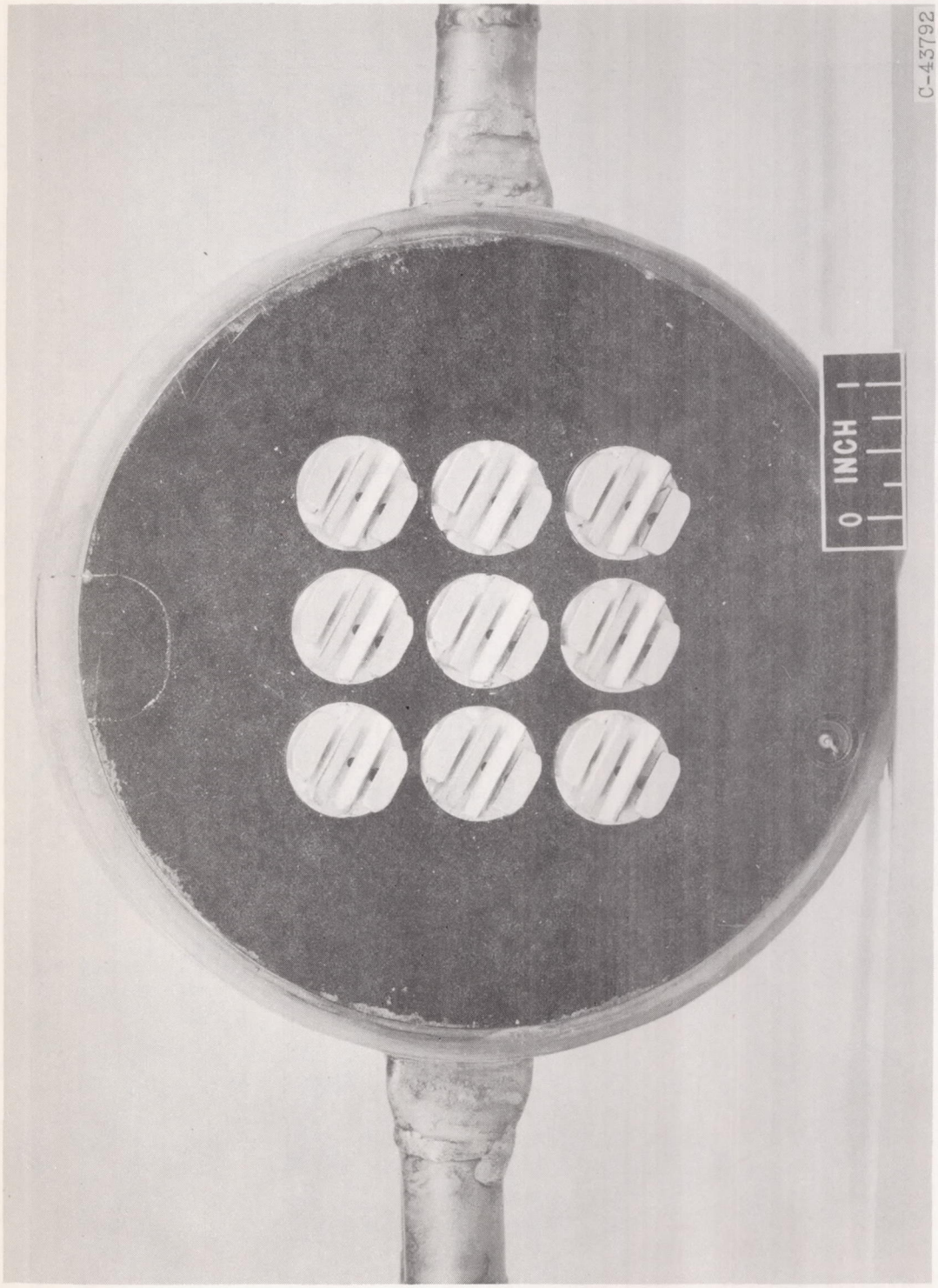
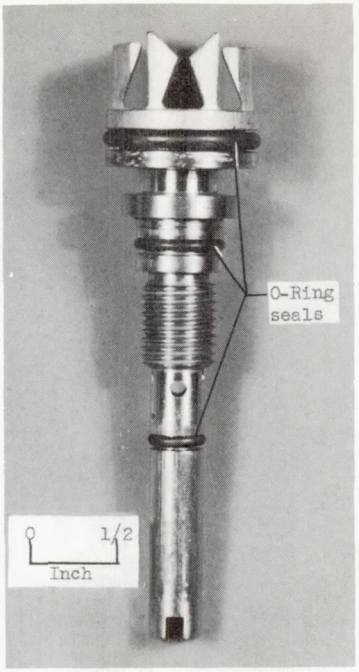
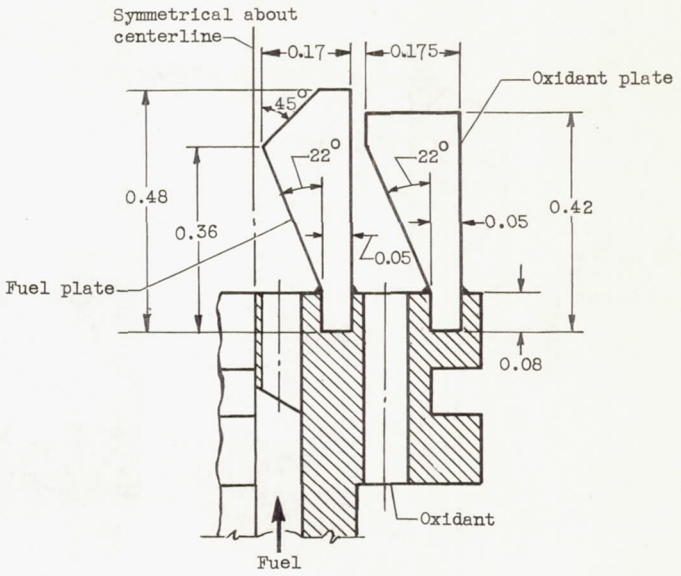
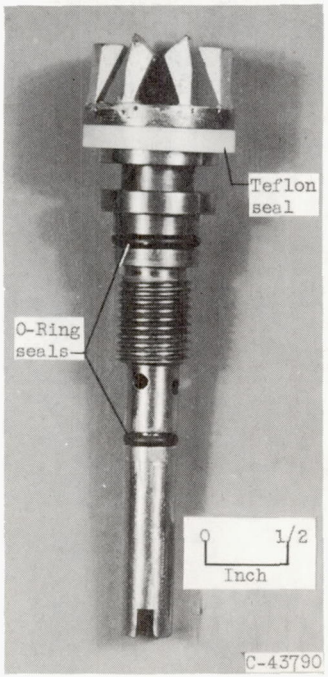


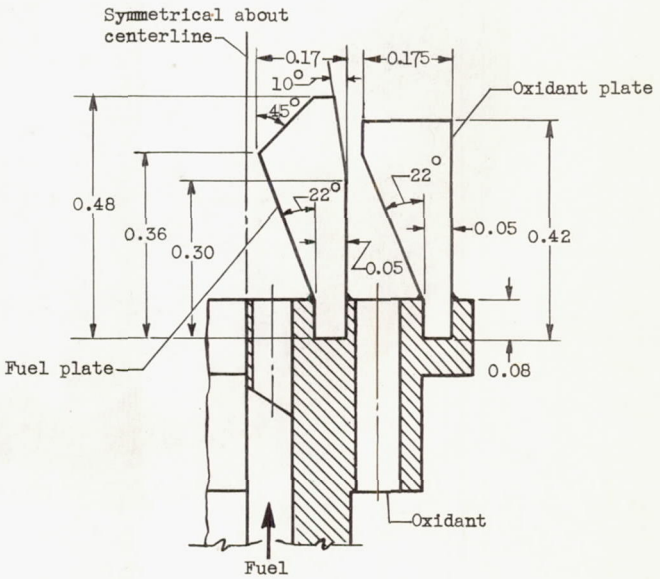
Figure 2. - Concluded. Exploded and assembled views of nine-element injector.





Parallel-sheets element





Impinging-sheets element

Figure 3. - Parallel-sheets and impinging-sheets elements. (All dimensions in inches except where noted.)

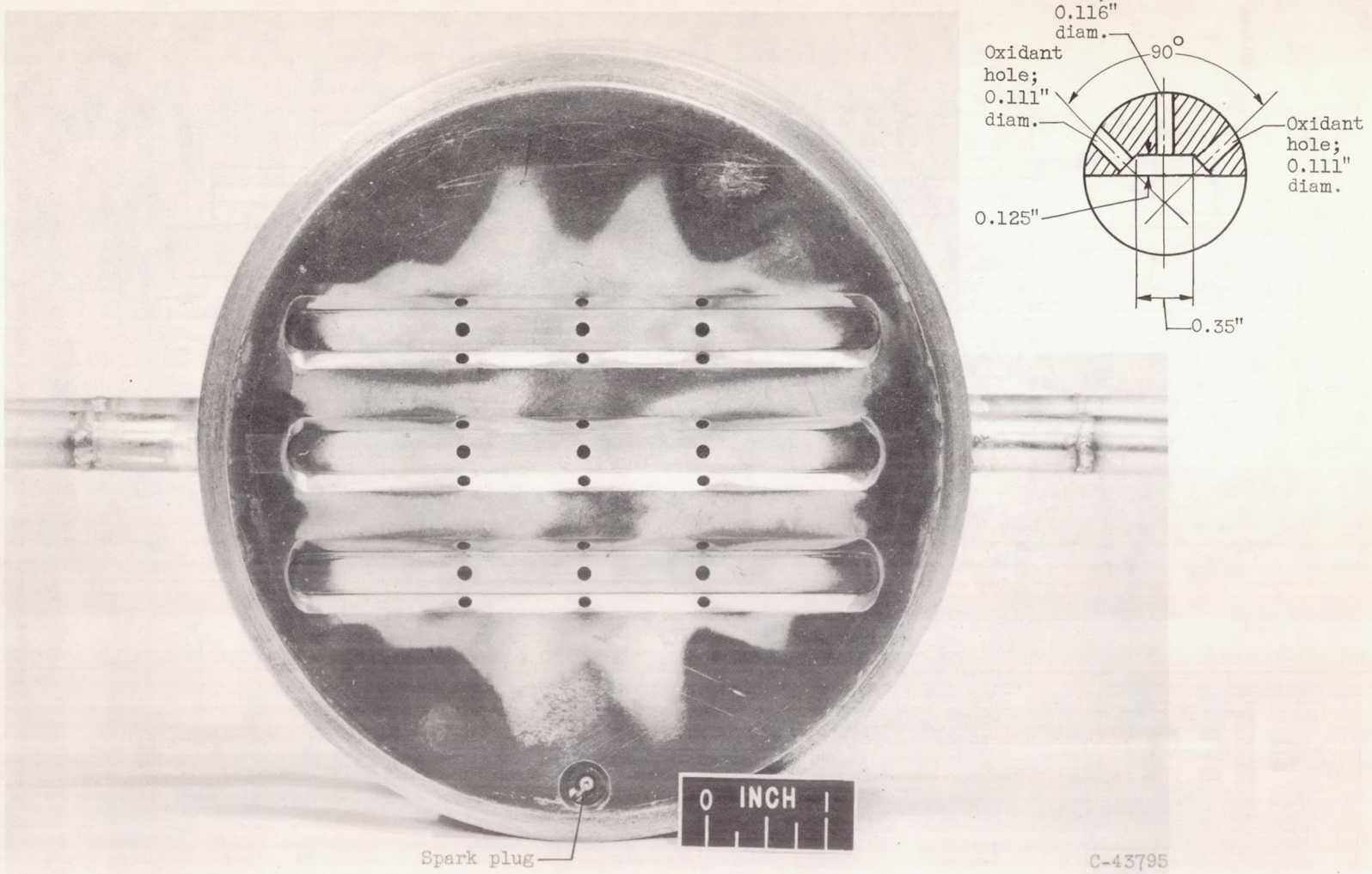
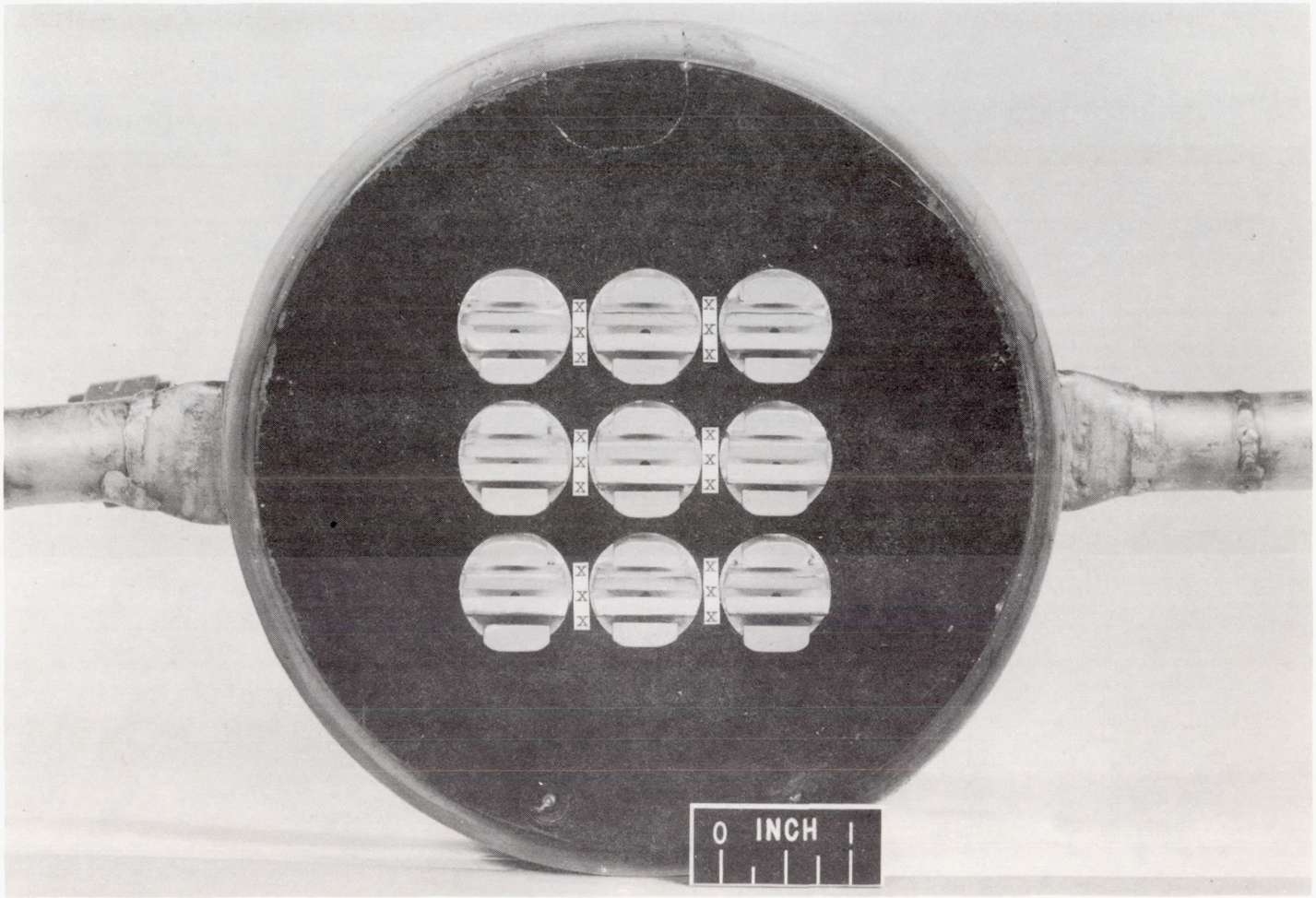


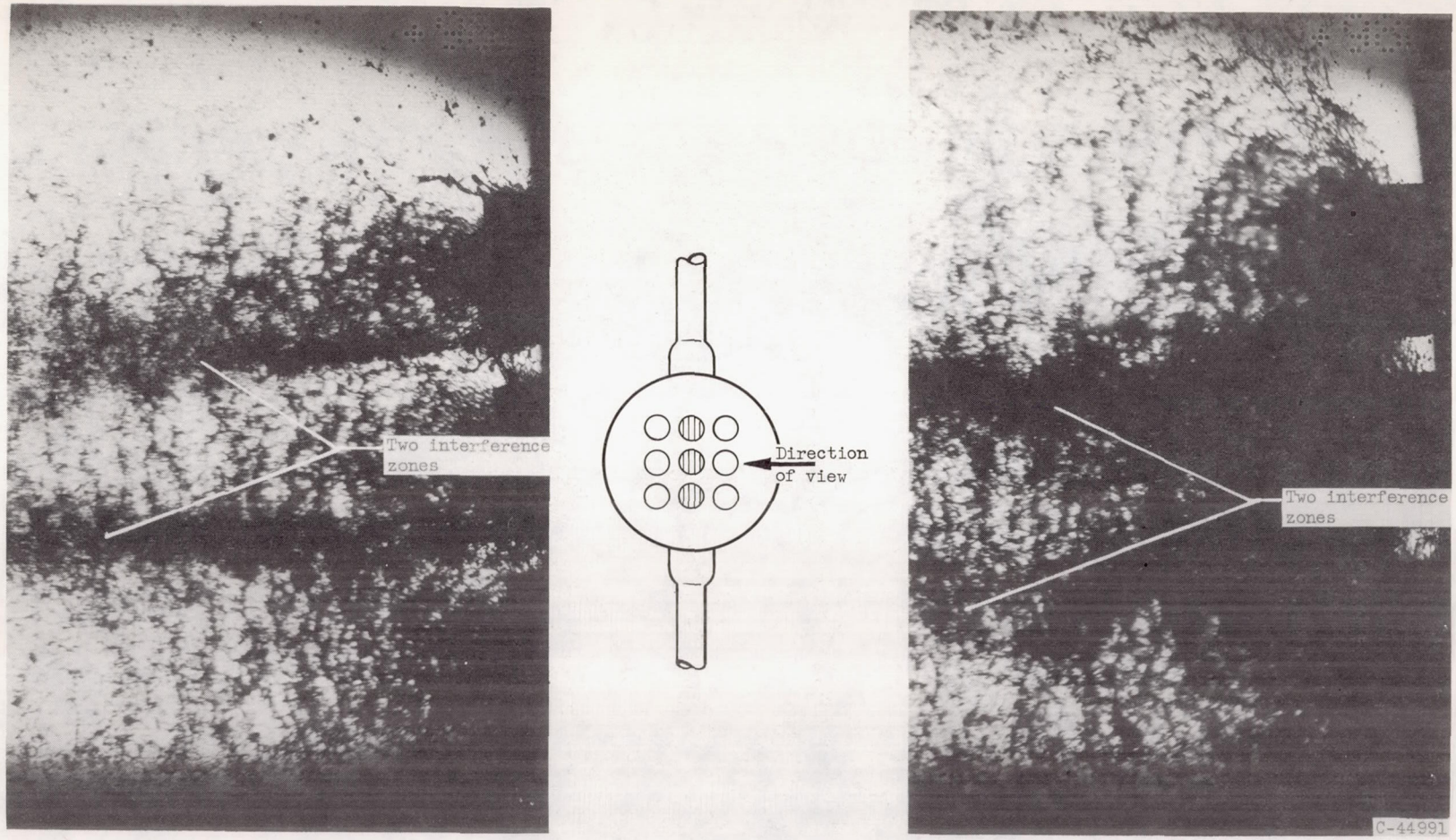
Figure 4. - Fixed-element, nine-unit impinging-jets injector with elements in butt orientation.



Total number of interference zones (denoted by x), 18

(a) Butt orientation.

Figure 5. - Various orientations of parallel-sheets elements and nine-element injector configuration and water-spray photographs.

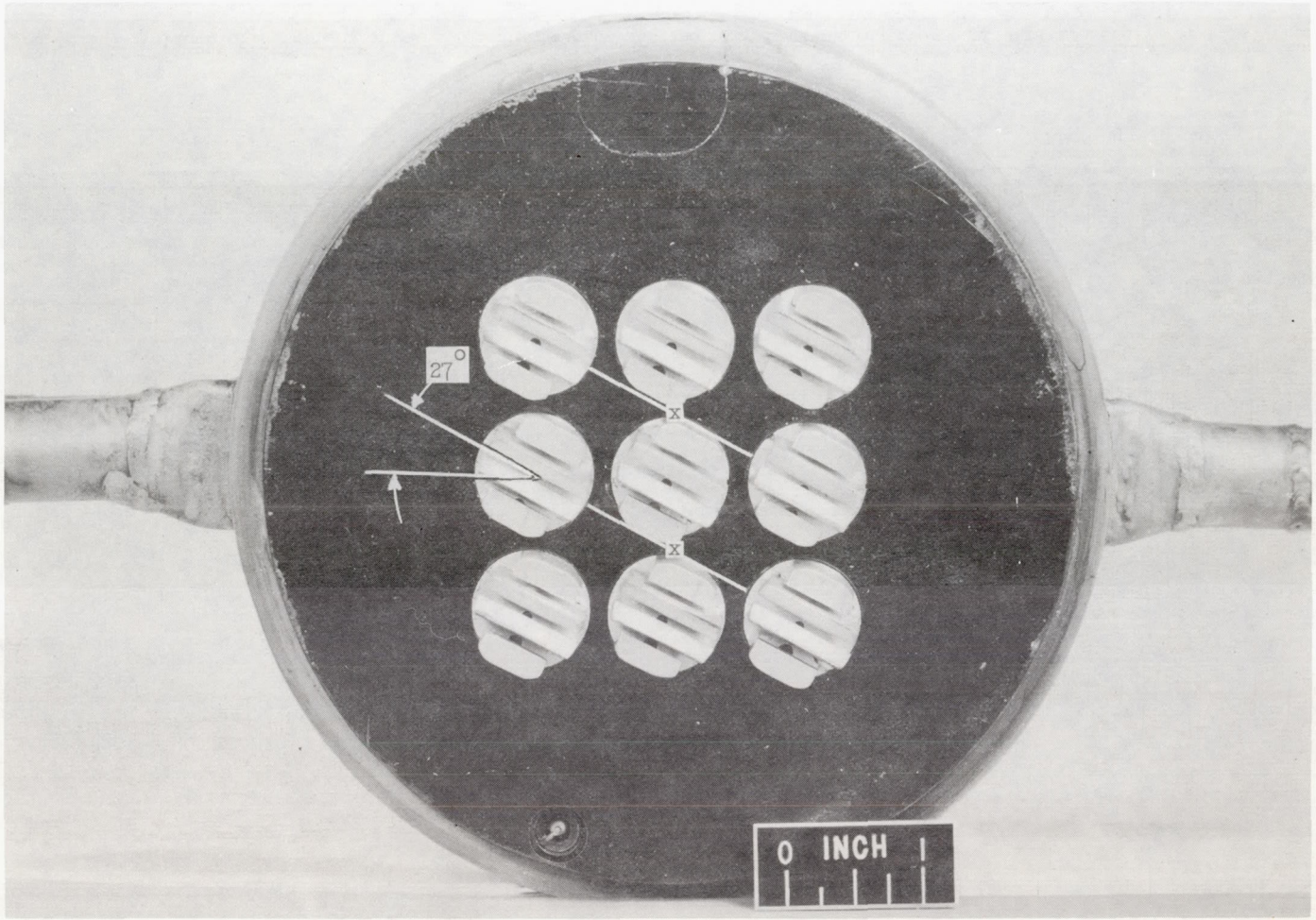


Fuel sprays only

Oxidant sprays only

(a) Concluded. Butt orientation.

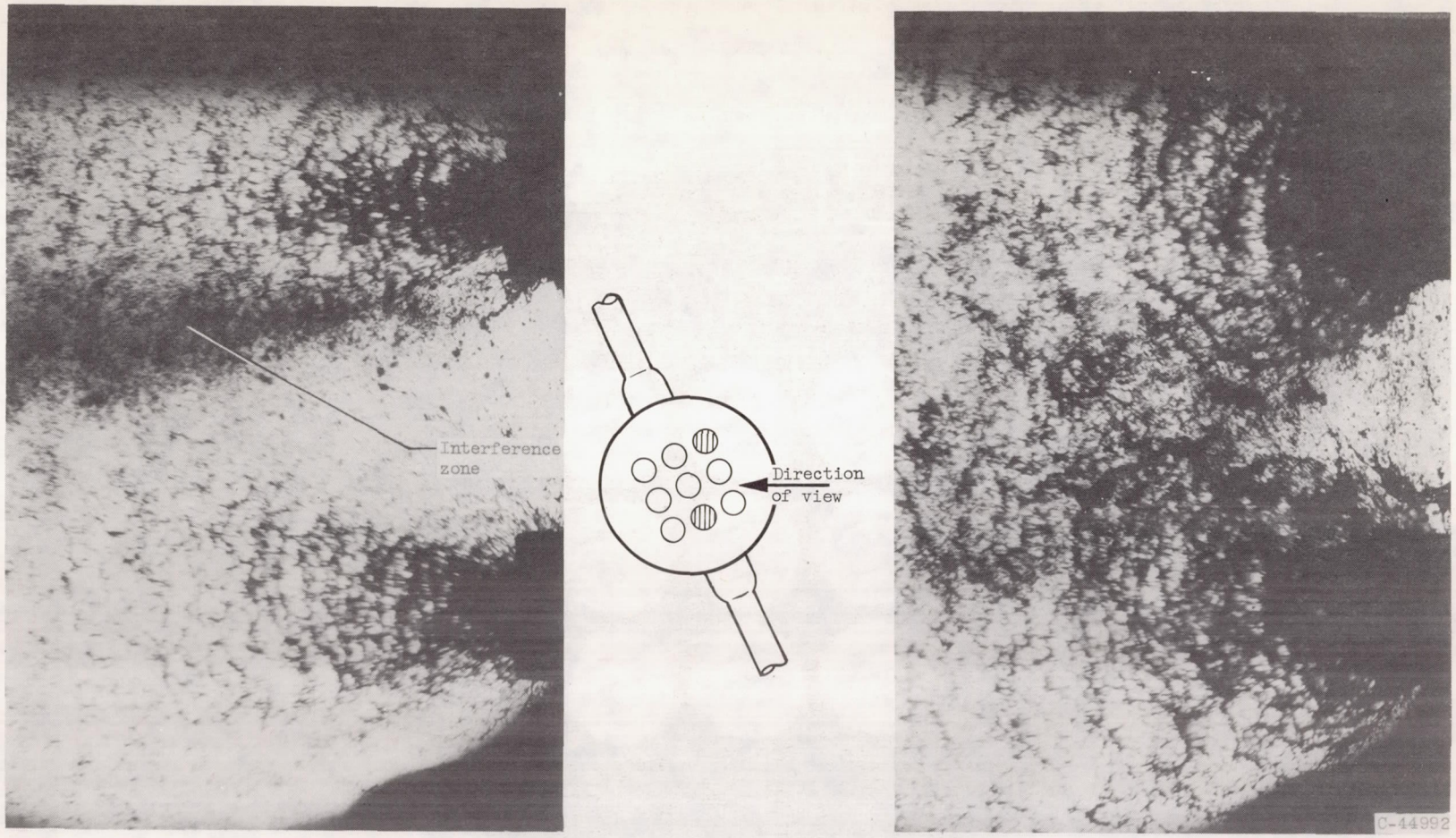
Figure 5. - Continued. Various orientations of parallel-sheets elements and nine-element injector configuration and water-spray photographs.



Total number of interference zones (denoted by x), 2

(b) 27° Orientation.

Figure 5. - Continued. Various orientations of parallel-sheets elements and nine-element injector configuration and water-spray photographs.

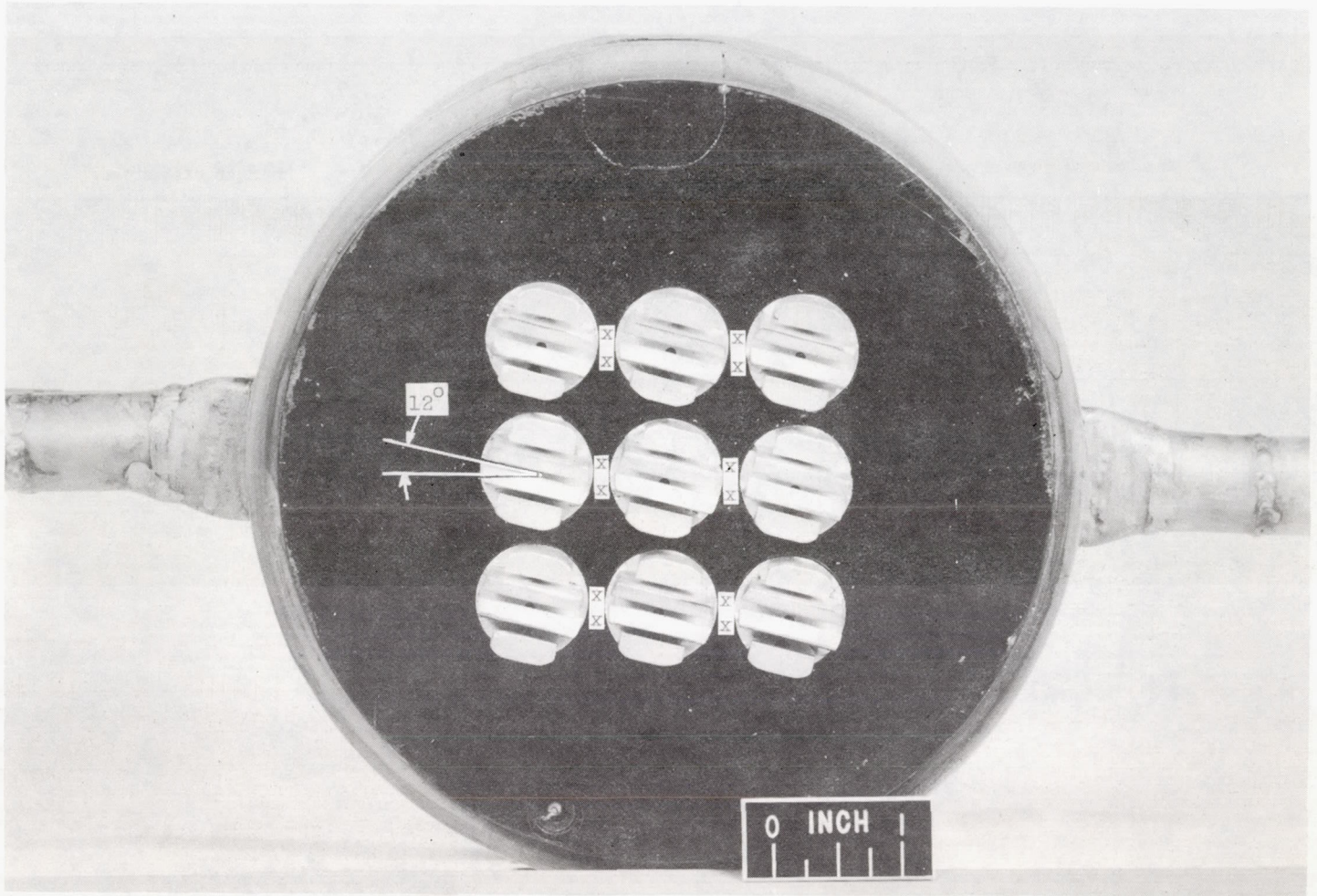


Fuel sprays only

Oxidant sprays only

(b) Concluded. 27° Orientation.

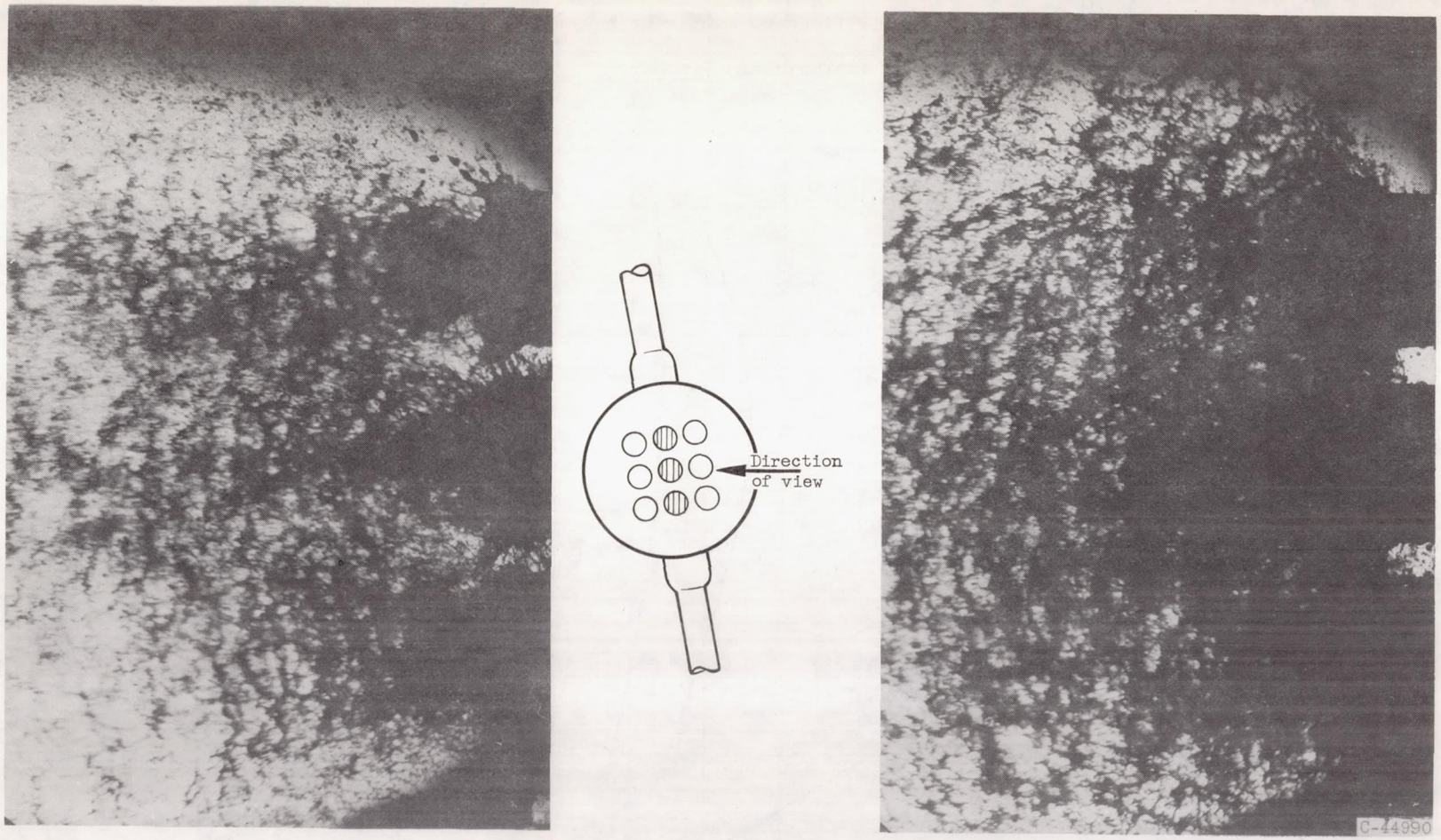
Figure 5. - Continued. Various orientations of parallel-sheets elements and nine-element injector configuration and water-spray photographs.



Total number of interference zones (denoted by x), 12

(c) 12° Orientation.

Figure 5. - Continued. Various orientations of parallel-sheets elements and nine-element injector configuration and water-spray photographs.



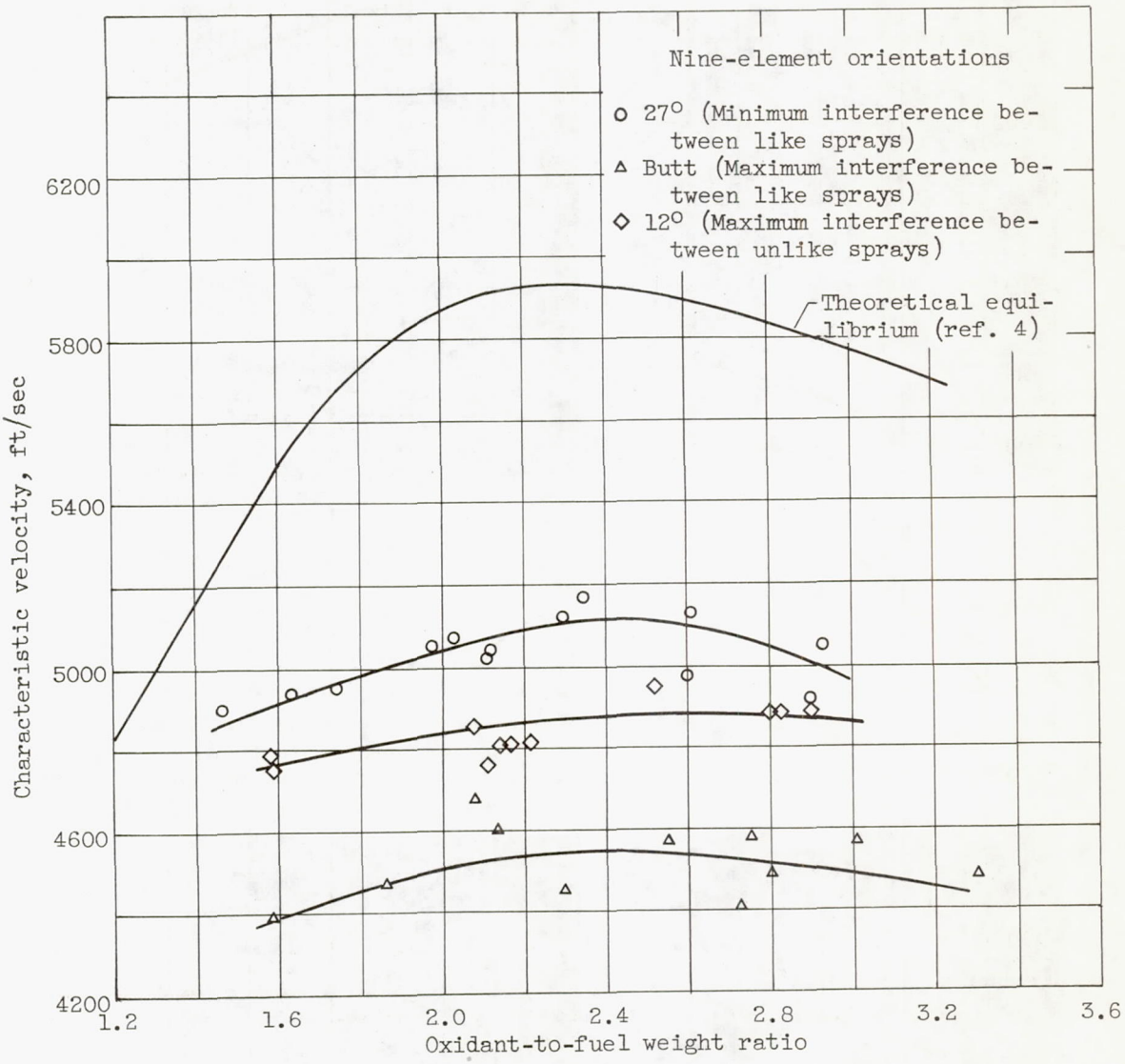
Fuel sprays only

Oxidant sprays only

(c) Concluded. 12° Orientation.

Figure 5. - Concluded. Various orientations of parallel-sheets elements and nine-element injector configuration and water-spray photographs.

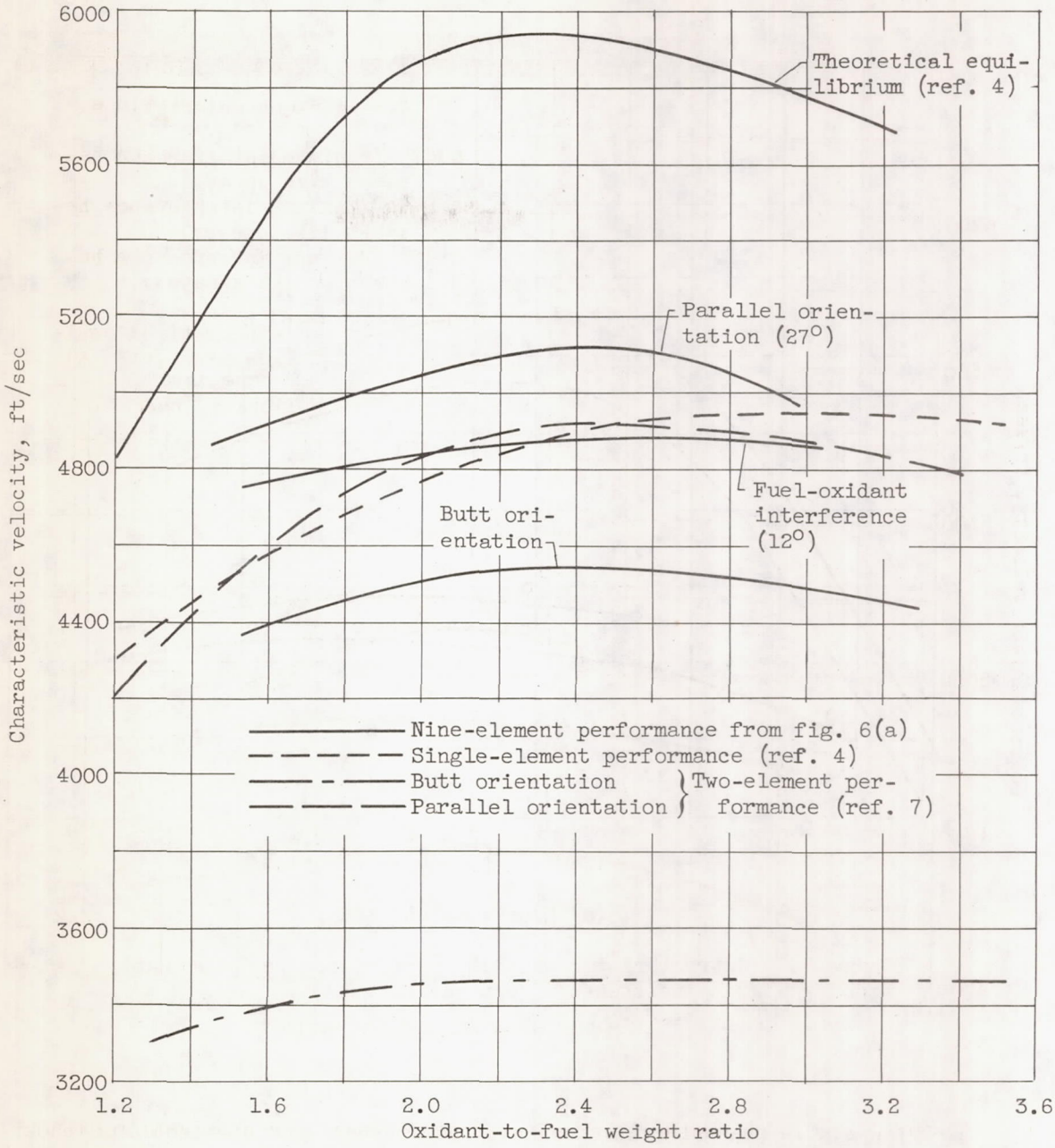
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(a) Nine-element study.

Figure 6. - Characteristic velocity performance for atomization without mixing (parallel-sheets injectors).

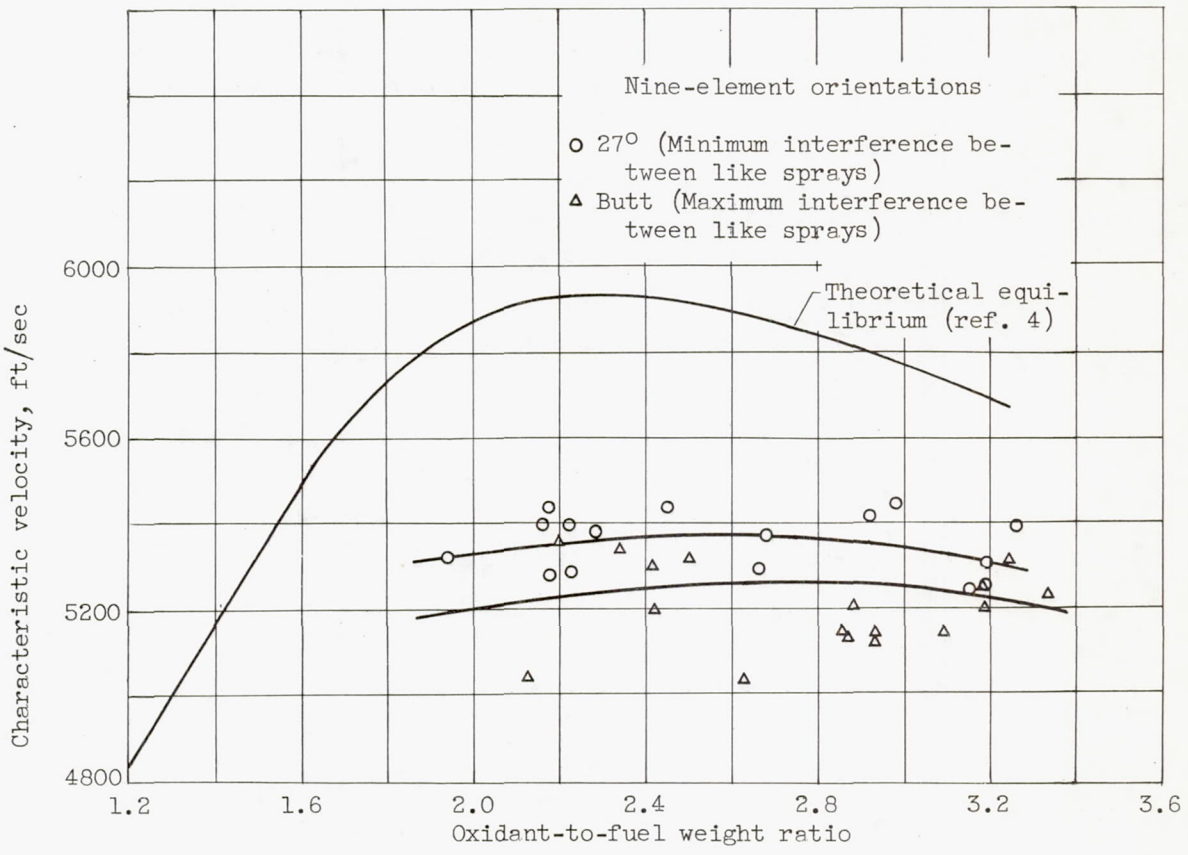
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(b) Single-, two-, and nine-element studies.

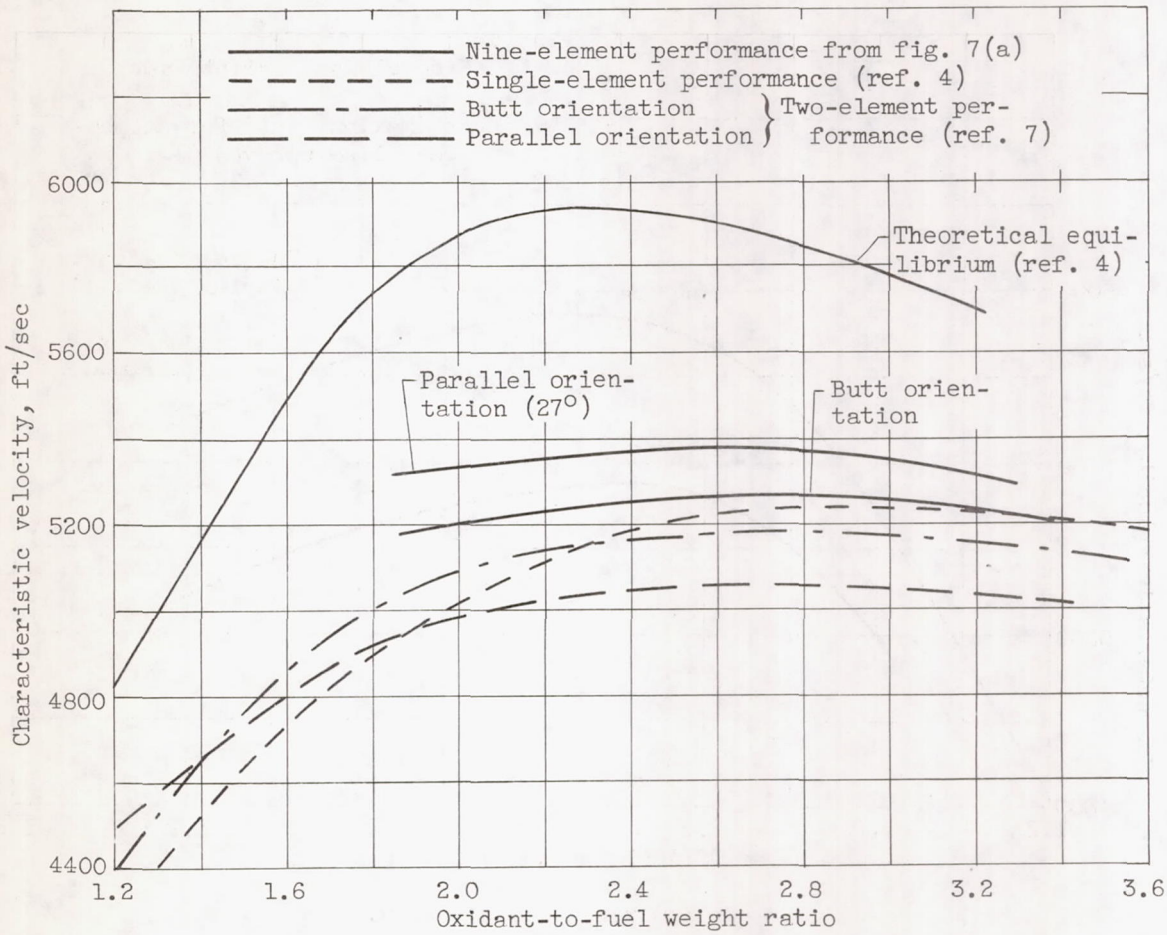
Figure 6. - Concluded. Characteristic velocity performance for atomization without mixing (parallel-sheets injectors).

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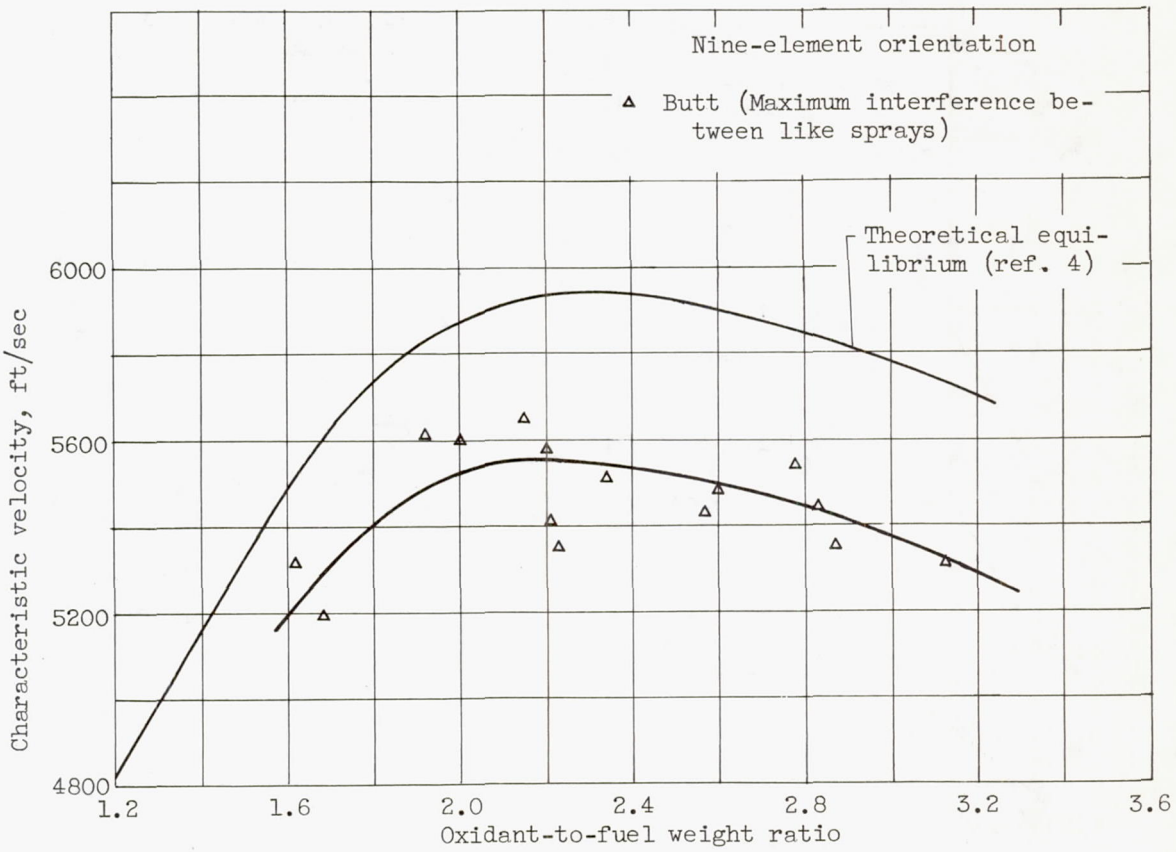
(a) Nine-element study.

Figure 7. - Characteristic velocity performance for atomization before mixing (impinging-sheets injectors).



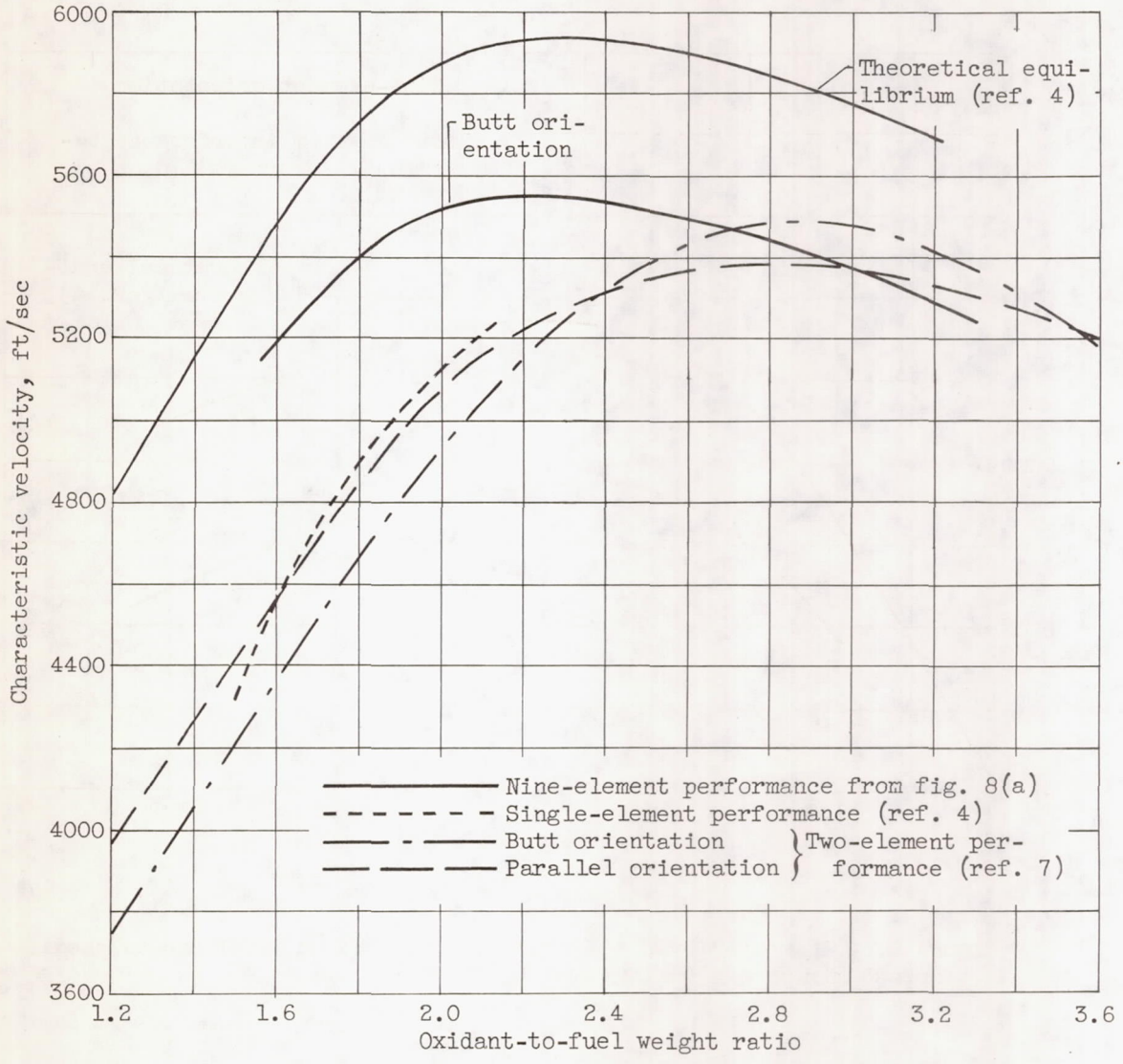
(b) Single-, two-, and nine-element studies.

Figure 7. - Concluded. Characteristic velocity performance for atomization before mixing (impinging-sheets injectors).



(a) Nine-element study.

Figure 8. - Characteristic velocity performance for simultaneous atomization and mixing (impinging-jets injector).



(b) Single-, two-, and nine-element studies.

Figure 8. - Concluded. Characteristic velocity performance for simultaneous atomization and mixing (impinging-jets injector).

NACA - Langley Field, Va.